

# Higgs Searches at the Tevatron <sup>a</sup>

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Recent preliminary results obtained by the CDF and DØ Collaborations on searches for the Higgs boson in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV at the Fermilab Tevatron collider are discussed. The data, corresponding to integrated luminosities of about  $1 \text{ fb}^{-1}$ , show no excess of a signal above the expected background in any of the decay channels examined. Instead, upper limits at 95% Confidence Level on the cross section are established. Further, a combined Standard Model Tevatron cross section limit is presented.

## 1 Introduction

The Higgs boson is the last missing particle in the Standard Model (SM). Its mass is not determined by the SM, there are however several experimental constraints which bound the Higgs mass to values which are within the reach of the Tevatron collider. Lower bounds are given from direct searches at LEP2. These results exclude Higgs masses below 114.4 GeV at the 95% Confidence Level (C.L.)<sup>1</sup>. An upper bound on the Higgs mass is obtained by global electroweak fits. Especially radiative corrections to the  $W$  mass from the Higgs and top quark play an important role. New precision measurements of the  $W$  mass<sup>2</sup> and the top mass<sup>3</sup> from the Tevatron favor a light SM Higgs boson and yield an upper value of 144 GeV at 95% C.L. (or 182 GeV if the LEP2 limit is included)<sup>4</sup>.

## 2 Experimental environment

The Higgs searches are crucially dependent on performance of the Tevatron accelerator and detectors. Both, CDF and DØ detectors are currently performing close to their optimal design values, taking data with an efficiency of about 90%. The present Tevatron performance is matching the design values in terms of the current weekly integrated and peak luminosity. As

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of today, more than  $2.5 \text{ fb}^{-1}$  have been delivered, with weekly integrated luminosity routinely reaching  $50 \text{ pb}^{-1}$ . If the accelerator keeps following the designed luminosity evolution, an integrated luminosity of about  $8 \text{ fb}^{-1}$  will be achieved by the end of 2009, increasing the potential for a Higgs discovery at the Tevatron significantly.

### 3 Standard Model Higgs searches

Production cross sections for the SM Higgs boson at the Tevatron are rather small. They depend on the Higgs mass and are about  $0.1 - 1 \text{ pb}$  in the mass range of  $100 - 200 \text{ GeV}$ . The largest production cross section comes from gluon fusion, where the Higgs is produced via a quark loop. The second largest cross section, almost an order of magnitude smaller, is the associated production with vector bosons. At the mass range covered by the Tevatron, below  $135 \text{ GeV}$  the highest branching ratio is given by the decay to  $b\bar{b}$  pairs and for masses above  $135 \text{ GeV}$  the Higgs boson decays mainly to  $WW$  pairs.

These production and decay properties lead to the following search strategy at the Tevatron:

- For masses below  $135 \text{ GeV}$  the main search channels are the associated productions with vector bosons where the Higgs decays into  $b\bar{b}$  pairs. In order to isolate the main background processes to these channels, an efficient b-tagging algorithm and a good dijet mass resolution are essential. The same final state produced via the gluon fusion process leads to a higher cross section but is overwhelmed by the huge multijet QCD background at a hadron collider.
- For masses above  $135 \text{ GeV}$  the search is mainly focused on the gluon fusion production process where the Higgs decays into  $WW$  pairs.

#### 3.1 $WH \rightarrow \ell\nu b\bar{b}$ , $\ell = e, \mu$

For SM Higgs searches the most sensitive production channel at the Tevatron for a Higgs mass below  $135 \text{ GeV}$  is the associated production of a Higgs boson with a  $W$  boson. Dominant backgrounds to the  $WH$  signal are  $W + \text{heavy flavor production}$ ,  $t\bar{t}$  and single-top quark production. Both, CDF and DØ performed cut based analyses with a rather similar approach. Both, electron and muon channels are studied here. The channels are separated in events having exactly one "tight" b-tagged jet (ST), and those having two "loose" b-tagged jets (DT) (with no overlap). The resulting four channels are analyzed independently to optimize the sensitivity and are later combined. Both experiments select events with isolated electrons or muons with  $p_T > 20 \text{ GeV}$ , require missing transverse energy above  $20 \text{ GeV}$  and two jets with  $p_T > 20 \text{ GeV}$  (DØ) or  $p_T > 15 \text{ GeV}$  (CDF). Cross section limits are derived from the invariant dijet mass distribution of the four individual analyses of each experiment and later combined. For  $m_H = 115 \text{ GeV}$  the observed (expected) limit is  $1.3 \text{ (1.1) pb}$  at DØ<sup>5</sup> and  $3.4 \text{ (2.2) pb}$  at CDF<sup>6</sup>, to be compared to the Standard Model cross section expectation of  $0.13 \text{ pb}$ . Thus the best expected measurement is a factor 8.8 higher than the SM expectation.

DØ analyzed this channel also with the Matrix Element technique to separate signal from background. Like in the cut based analysis the four channels ( $e, \mu, \text{ST}, \text{DT}$ ) are analyzed separately and later combined. The matrix-element-based technique attempts to make use of all the available kinematic information in the event to separate signal and background. Therefore leading order Matrix Elements are used to compute the event probabilities for signal and background. The present selection criteria is based on the single top search and will be optimized in the future. Although this selection is not optimal for  $WH$ , the sensitivity of this search is similar to the sensitivity of the cut-based analysis and will improve with an optimized selection. For  $m_H = 115 \text{ GeV}$  the observed (expected) limit is  $1.7 \text{ (1.2) pb}$  with this present approach<sup>7</sup>. Limits for other Higgs masses together with the cut-based results are displayed in Fig.1.

### 3.2 $ZH \rightarrow \ell b \bar{b}$ , $\ell = e, \mu$

Similarly to  $WH$  the Higgs boson can be produced associated with the  $Z$  boson. First we focus on the channel where the  $Z$  boson decays to a pair of electrons or muons with opposite sign. Here the  $Z$  boson is reconstructed and identified from a pair of high  $p_T$  leptons with an invariant mass constraint. Events are required to have b-tagged jets. The dominant backgrounds result from the associated production of a  $Z$  boson with jets, among which the  $Zb\bar{b}$  production is an irreducible background. Other main backgrounds are  $t\bar{t}$ ,  $WZ$ ,  $ZZ$ , and multijet production from QCD processes.

In the search at DØ at least two b-tagged jets are required. Cross section limits are then derived from the dijet invariant mass distribution within a search window. At CDF only 1 b-tagged jet is required. After this, a two dimensional Neural Network discriminates against the two largest backgrounds which are  $Z + \text{jets}$  and  $t\bar{t}$ . Limits are derived from the Neural Network distribution. For  $m_H = 115$  GeV the observed (expected) limit is 2.7 (2.8) pb at DØ<sup>8</sup> and 2.2 (1.9) at CDF<sup>9</sup>, to be compared to the Standard Model cross section expectation of 0.08 pb.

### 3.3 $ZH \rightarrow \nu \nu b \bar{b}$ , $WH \rightarrow (\ell^\pm) \nu b \bar{b}$

The  $ZH \rightarrow \nu \nu b \bar{b}$  channel benefits from the large  $Z \rightarrow \nu \nu$  branching ratio. However it is challenging at hadron colliders due to the absence of visible leptons and the presence of only two jets in the final state. The two b-jets from the Higgs are boosted along the direction of the Higgs momentum and so tend to be more acoplanar than the dijet background. There are two major sources of background: physics backgrounds such as  $Z + \text{jets}$ ,  $W + \text{jets}$ , electroweak diboson production or top quark production with missed leptons and jets and the instrumental background resulting from calorimeter mismeasurements which can lead to high  $E_T$  signals with the presence of jets from QCD processes.

A result on this search channel was presented from CDF. Selecting events with a large  $E_T > 75$  GeV and high  $p_T$  b-tagged jets (leading jet  $p_T > 60$  GeV), vetoing events with isolated leptons or where the missing  $E_T$  is aligned in  $\phi$  with jets eliminate much of the physics background. Two separate analyses are optimized for one or two b-tagged samples and later combined. Since the  $WH$  channel with an undetected lepton has the same signature those events are taken into account in this search channel. For  $m_H = 115$  GeV the expected limit at CDF is a factor 15 higher than the Standard Model expectation<sup>10</sup>.

### 3.4 $H \rightarrow WW^{(*)} \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ , $\ell = e, \mu$

At Higgs masses above 135 GeV the biggest branching ratio is the decay to  $WW$  pairs. With only leptons and missing energy in the final state the main background is  $WW$  production without a large overlapping QCD background. Both, CDF and DØ analyzed this channel for the three combinations of electron and muon final states. Later the cross section limits have been combined.

The search strategy is to look for two high  $p_T$ , isolated, opposite sign leptons, require large missing transverse energy and veto on events with jets. Finally, the spin correlations in the decay of the Higgs boson are used. The leptons of the Higgs decay tend to have a small opening angle, whereas leptons from most of the backgrounds are expected to be back-to-back. Thus a cut on the opening angle between the leptons in the transverse plane  $\Delta\phi_{\ell\ell}$  is mainly used to discriminate against the dominant  $WW$  background. Since the Higgs mass cannot be directly reconstructed due to the neutrinos in the final state, the cross section limit is derived from the  $\Delta\phi_{\ell\ell}$  distribution. For  $m_H = 160$  GeV, which yields the best sensitivity, the expected limit at CDF<sup>11</sup> is a factor 6 and at DØ<sup>12,13</sup> a factor of 5 higher than the Standard Model expectation.

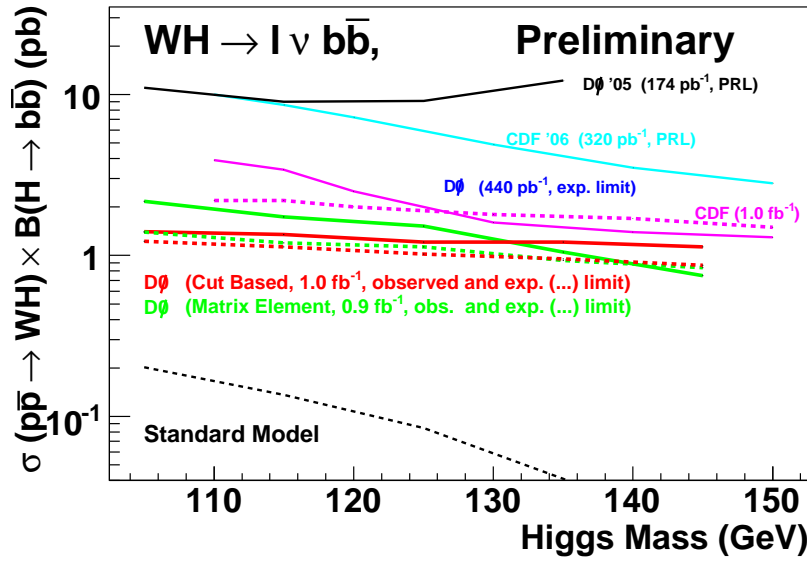


Figure 1: 95% C.L. upper cross section limits on  $WH$  production from the cut-based CDF and  $D\bar{O}$  measurements and from the matrix-element-approach by  $D\bar{O}$ .

### 3.5 Combined Standard Model Higgs limits

The above presented channels can be combined which leads to a much more sensitive cross section limit throughout the whole discussed mass range. Both,  $D\bar{O}$  and CDF released results on the SM Higgs combination, the obtained results can be found in <sup>14</sup>. A further, important increase of the sensitivity can be gained from a combination of the CDF and  $D\bar{O}$  results. Such a first Tevatron combination limit was released Summer 2006, the result is plotted in Fig.2. The expected combined limits are a factor of 7.5 at  $m_H = 115$  GeV and a factor of 4 at  $m_H = 160$  GeV away from the Standard Model expected cross sections. It should be stressed that this result does not include CDF's new  $1 \text{ fb}^{-1}$  high mass results and it does not include any of  $D\bar{O}$ 's new  $1 \text{ fb}^{-1}$  low mass results yet. Further significant improvements are expected when all the  $1 \text{ fb}^{-1}$  results will be included. Such a new Tevatron combination is planned for the Summer 2007.

## 4 MSSM Higgs searches

The Minimal Supersymmetric Standard Model (MSSM) predicts two Higgs doublets leading to five Higgs bosons: a pair of charged Higgs boson ( $H^\pm$ ); two neutral CP-even Higgs bosons ( $h, H$ ) and a CP-odd Higgs boson ( $A$ ). At tree level, the Higgs sector of the MSSM is fully described by two parameters, which are chosen to be the mass of the CP-odd Higgs,  $m_A$ , and  $\tan\beta$ , the ratio of the vacuum expectation values of the two Higgs doublets. The Higgs production cross-section is enhanced in the region of low  $m_A$  and high  $\tan\beta$  due to the enhanced Higgs coupling to down-type fermions. This makes it possible to search in the MSSM for  $\tau\tau$  final states, which would be very challenging in the SM due to the large irreducible background of  $Z \rightarrow \tau\tau$ . In the low  $m_A$ , high  $\tan\beta$  region of the parameter space, Tevatron searches can therefore probe several MSSM benchmark scenarios extending the search regions covered by LEP <sup>15</sup>.

Both, CDF and  $D\bar{O}$  performed a search for the neutral MSSM Higgs decaying to  $\tau$  pairs, where one of the  $\tau$ -leptons is decaying in the leptonic and the other one in the hadronic mode.  $D\bar{O}$ 's result covers so far only the  $\mu$ -channel, CDF's result is a combination of the electron and

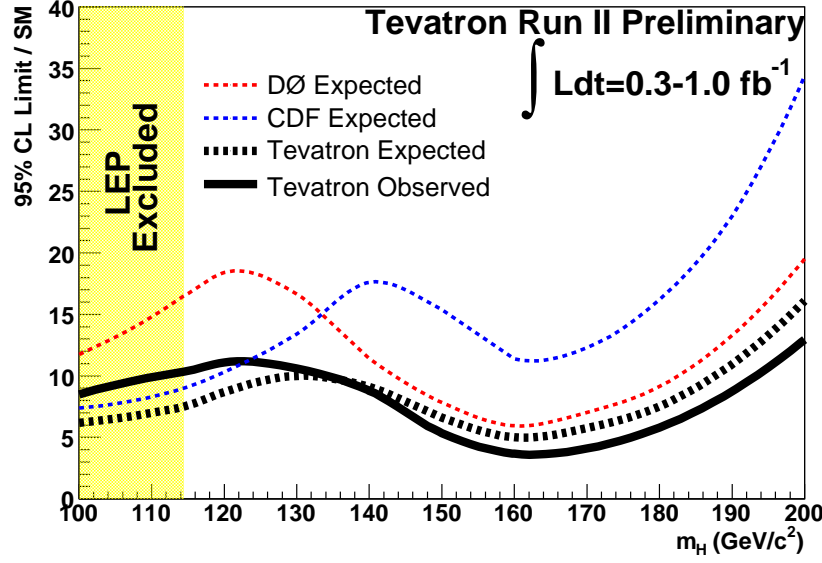


Figure 2: Combined DØ and CDF upper limits on Standard Model Higgs boson production.

muon channels, including  $\tau_e\tau_\mu$ .

A set of Neural Networks (NN) is used at DØ to discriminate  $\tau$ -leptons from jets. An isolated muon is required, separated from the hadronic  $\tau$  with opposite sign. A cut on the visible  $W$  mass removes most of the remaining  $W$  boson background. Further optimized NNs are used for signal discrimination. In the cross section limit calculation the output of the NNs for different tau types is used.

CDF uses a variable cone size algorithm for  $\tau$  discrimination. An isolated muon or electron is required, separated from the hadronic  $\tau$  with opposite sign. Most of the  $W$  background is removed by a requirement on the relative directions of the visible  $\tau$  decay products and the missing transverse energy. Cross section limits are derived from the visible mass distribution.

For both experiments the data is consistent with the background only observation. Exclusion regions in the  $\tan\beta - m_A$  plane can be derived for different MSSM benchmark scenarios. Both experiments obtained similar results<sup>16,17,18</sup>. In the region of  $90 < m_A < 200$  GeV,  $\tan\beta$  values larger than 40-60 are excluded for the no-mixing and the  $m_h^{max}$  benchmark scenarios. Examples of such exclusion regions are shown in Fig.3. In CDF's result the observed limits are weaker than the expectations due to some excess of events in the data sample with a significance of approximately  $2\sigma$ .

## 5 Perspectives

Today some single channels have cross section limits similar to the combined Tevatron results obtained half a year ago. With Tevatron's excellent performance matching the designed delivered weekly luminosities, a significant amount of sensitivity will be gained by an increase of the luminosity by about a factor of 8. There is already 2.5 times more data on tape than used for the presented results. In addition, the inclusion of more channels in the Higgs search (for example  $\tau$ -final states) will gain additional sensitivity. Dijet mass resolution, b-tagging and simulation are important ingredients for Higgs searches and both experiments are continuously improving at these scopes. Still a lot of improvements are expected in analyses techniques. Especially the use of multivariate techniques, like Neural Networks, Decision Trees and Matrix Element analyses

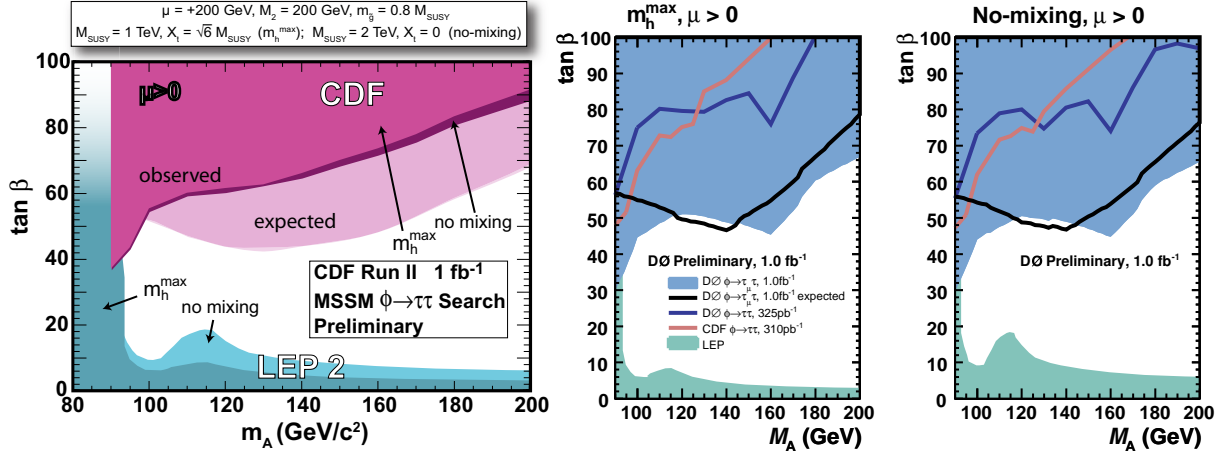


Figure 3: Excluded regions by the CDF and DØ experiments in the  $\tan \beta$ - $m_A$  plane for  $\mu < 0$  in the  $m_h^{max}$  and the no-mixing scenario.

shall bring further important improvements. DØ's recent evidence for Single Top production and CDF's  $WZ$  observation is an important milestone in the use of these techniques to discriminate very low rate signals in the presence of substantial backgrounds.

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